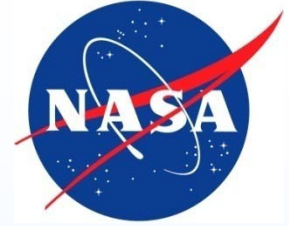


NEPP Electronic Technology Workshop June 2011

National Aeronautics
and Space Administration



Capacitor Test, Evaluation, and Modeling within NEPP.

**“Why Ceramic Capacitors Fracture during
Manual Soldering and How to Avoid Failures”.**

Alexander Teverovsky

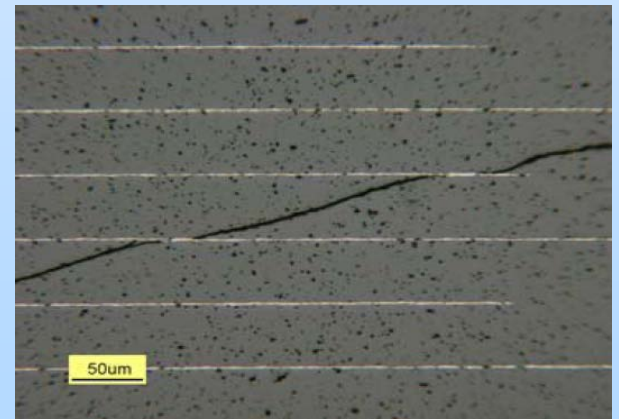
Dell Services Federal Government, Inc.

**work performed for NASA Goddard Space Flight Center,
Parts, Packaging, and Assembly Technologies Office,
Code 562**

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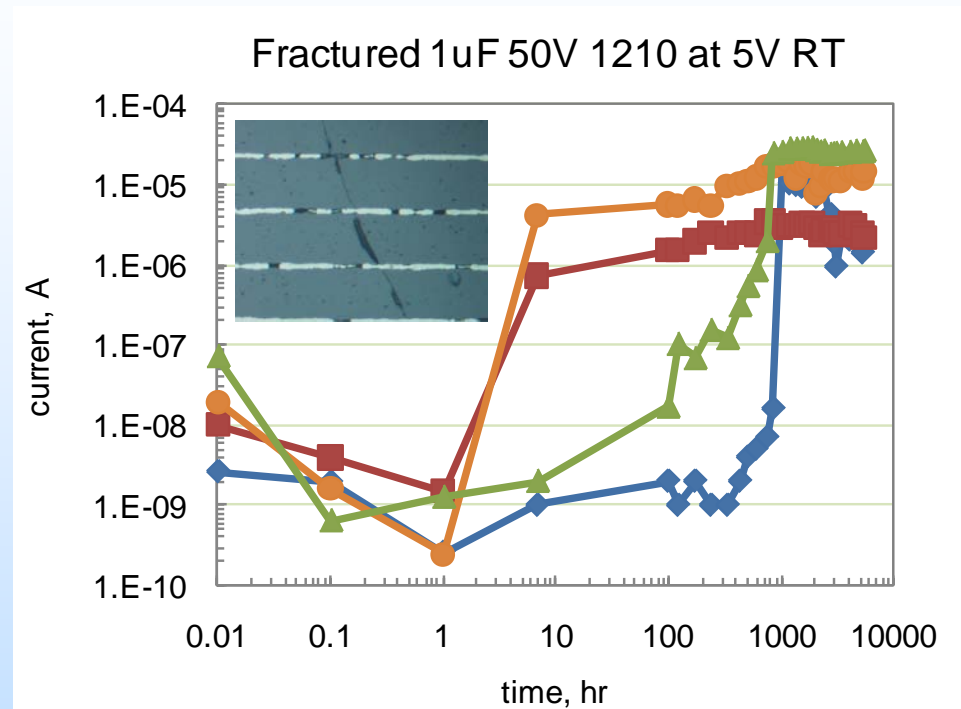
Outline

- ❑ Why MLCCs crack during manual soldering?
Workmanship and parts issues.
- ❑ Do existing qualification requirements assure crack-free soldering?
 - MIL-spec Thermal Shock (TS) testing.
 - MIL-spec Resistance to Soldering Heat (RSH) test.
- ❑ What test can assure reliable soldering?
 - Mechanical characteristics of ceramics.
 - Comparison of three TS techniques: LND, TSD, and IWT.
- ❑ Simulation of TS conditions.
- ❑ Conclusion/recommendations.
- ❑ NEPP plans for FY11/12.



Background and Purpose

- ❑ Cracking in MLCCs is an old problem, goes back to 1970s.
- ❑ Crack as a time bomb.
- ❑ Derating does not help.
- ❑ “Brittle ceramic” + “soldering-induced thermo-mechanical stress” = crack?
- ❑ The problem will stay with us, but it can be mitigated.

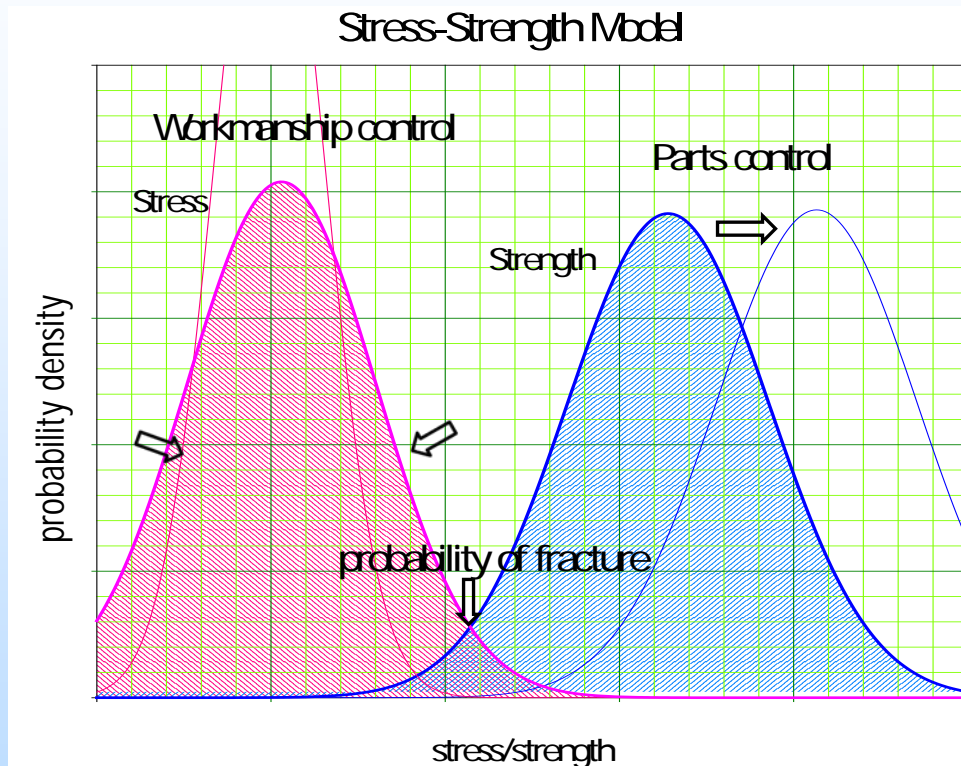


Purpose:

- ❑ Better understand the reasons of fracturing of large MLCCs under manual-soldering-induced thermal shock conditions;
- ❑ Suggest mitigating measures.

Probability of MLCCs Cracking

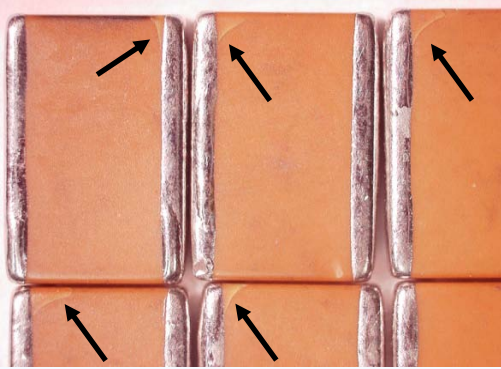
Failure criteria: $\sigma > S$



Probability of failure:

$$P = \int_{-\infty}^{+\infty} f(\sigma) \times \left[\int_{-\infty}^{\sigma} f(S) dS \right] d\sigma$$

- Assuring that the level of soldering stresses is at the acceptable level is a workmanship issue and should be achieved by reinforcing compliance with the guidelines.
- Assuring robustness to soldering stresses is a part issue and should be achieved by adequate qualification tests.

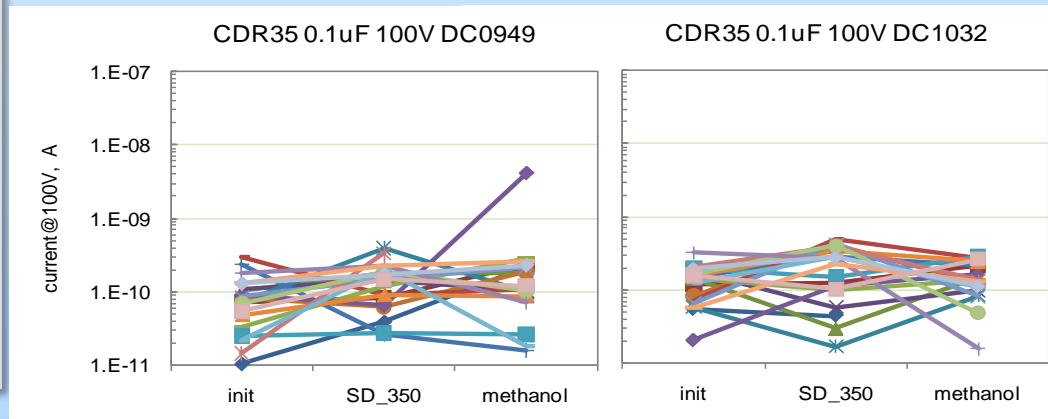


Can Parts and Workmanship Issues be Discriminated?

- ❑ A lot of 1825 X7R capacitors had multiple fractures after manual soldering. The board was reworked using another lot of capacitors, and no fracturing was observed.
- ❑ Was a technician more careful with the replacement lot, or two lots had different susceptibility to cracking?

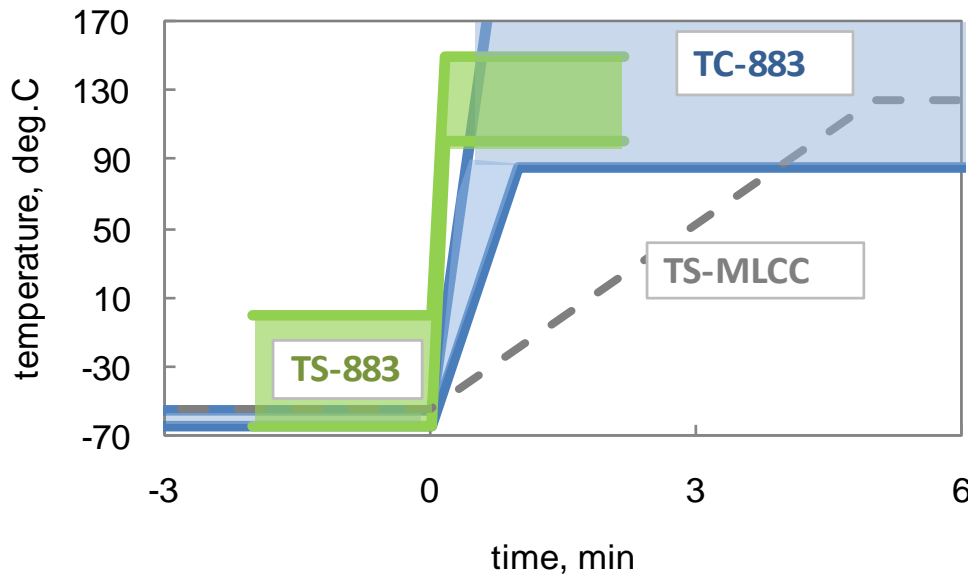
- ❑ Mechanical and electrical characteristics of two lots were similar.
- ❑ TSD test showed 55% fracturing for DC0949 and 0% for DC1032.
- ❑ One part in DC0942 failed post_TSD methanol test.
- ❑ This is a part issue.

LDC	VH, GPa	STD VH	K1C, MPa*m ^{0.5}	STD K1C
DC0949	12.7	1.98	1.16	0.23
DC1032	10.4	1.42	1.10	0.09



Thermal Shock Testing That Does not Create TS Conditions

TS and TC per MIL-STD-883 and
TS for MLCCs



MIL-883

TC, TM1010: air to air;

TS, TM1011: liquid to liquid

MIL-PRF-55681 (chip)

TS : air to air

☐ Difference between TC and TS:

- results of TC depend on $\Delta T = T_{\max} - T_{\min}$ and CTE mismatch;
- results of TS depend on temperature gradient across the part.

☐ TS conditions for MLCCs are less stressful than TC per MIL-883.

☐ Were any failures of MLCCs due TS testing ever observed?

Thermal Shock Testing

Spec.	Part type	TS testing	Comments
MIL-PRF-55681	ER and non-ER chip capacitors.	Qual. inspection (TS and immersion): 18 ⁽¹⁾ . Test cond. A (M202) but at 125C.	No TS during Gr. A insp. Qual: only 5c from -55C to +125C and 2 cycles of immersions from tap water at 65C into salty water at RT.
MIL-PRF-123	Capacitors for space and other high rel. applications.	Gr. A inspection: 20c. Qual. Inspection: 186 samples, 100 c. Gr.B insp.: 100c. cond. A but at 125C.	Qual: 100 cycles from -55C to +125C.

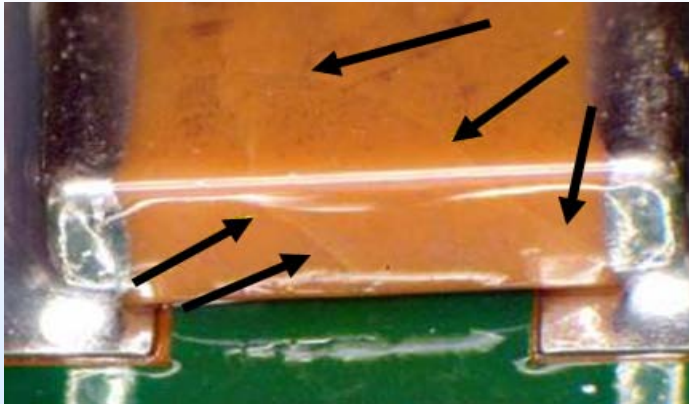
- ❑ Existing TS testing do not cause any significant thermo-mechanical stresses and does not simulate soldering conditions.
- ❑ MIL MLCCs cannot be used in hybrid microcircuits that require 100 TC between -65 °C and +150 °C without additional testing.

Resistance to Soldering Heat

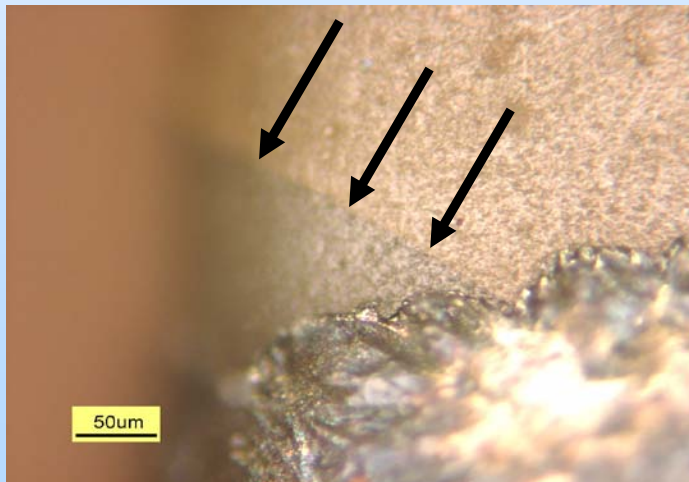
Spec.	Part type	RSH test	Comments
MIL-PRF-55681	ER and non-ER chip capacitors.	QCI: 9(1) Test cond. J (M202) (convection reflow), except with only one heat cycle.	Precaution for mounting: "... will not be the cause of, nor contribute to, failure of any test for which it may be used". One cycle to 235°C.
MIL-PRF-123	Capacitors for space and other high rel. applications.	QCI: 12(1) Test cond. B: 2 times. Solder T=230°C, 5 sec.	Manufacturers are using this test at 260°C and higher

- ☐ Existing requirements mostly follow the guidelines for safe soldering conditions and are relaxed compared to MIL-STD-202.
- ☐ The test does not simulate possible worst case soldering conditions and is not sufficient to reveal potentially weak lots of capacitors.
- ☐ None of the MIL specs for capacitors uses soldering iron test per MIL-STD-202, TM210 (350C, soldering pad, 5 sec).

Parts Control to Assure Reliable Soldering of MLCCs



- ❑ MIL specifications for ceramic capacitors do not assure crack-free soldering.
- ❑ Likely for this reason manufacturers warn against hand soldering of large capacitors:
“Never use soldering irons for parts with a case size of more than 1210”
J. Maxwell
- ❑ Are there mechanical characteristics and/or test methods that might assure robust manual soldering of MLCCs?

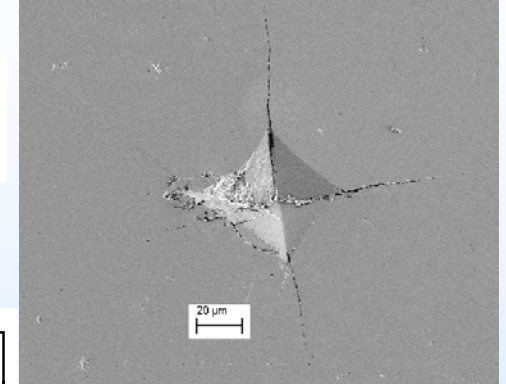


Mechanical Characteristics of Ceramics

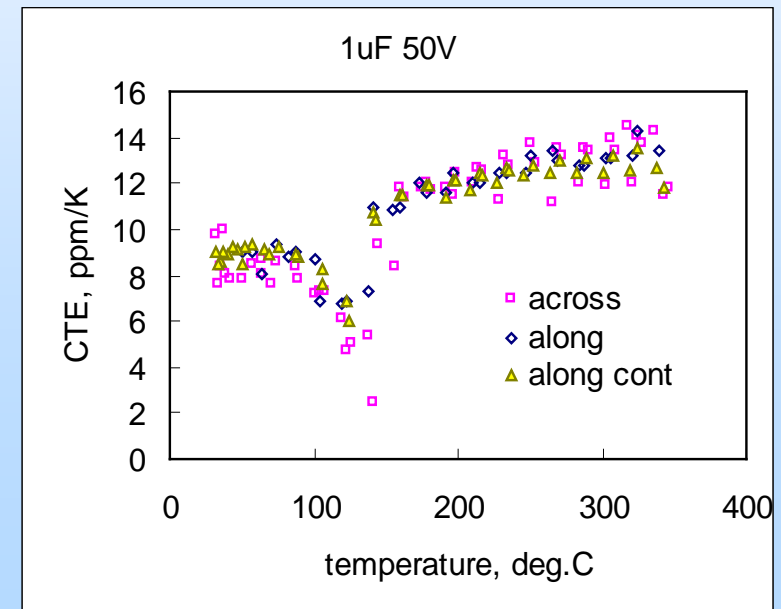
- Mechanical behavior of the parts was characterized by measurements of Vickers hardness, VH, fracture indentation toughness, K_{1C}, and CTE.

$$VH = \frac{1.854 \times P}{D^2}$$

$$K_{1c} = \zeta \left[\frac{E}{H} \right]^{0.5} \left[\frac{P}{c^{1.5}} \right]$$



- CTE values in X7R capacitors measured perpendicular to the plates were ~10% greater than along the plates.
- The anisotropy is likely due to built-in compressive stresses.
- Average CTE_{x1} = 9.6 at STD=1.2 and CTE_{x2} = 12.4 at STD=0.3

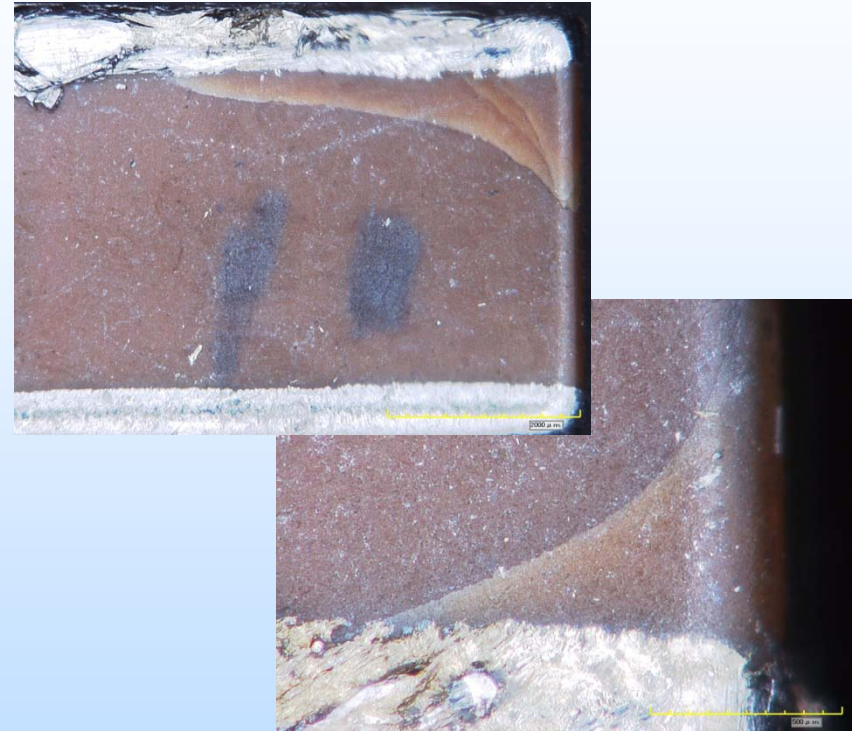
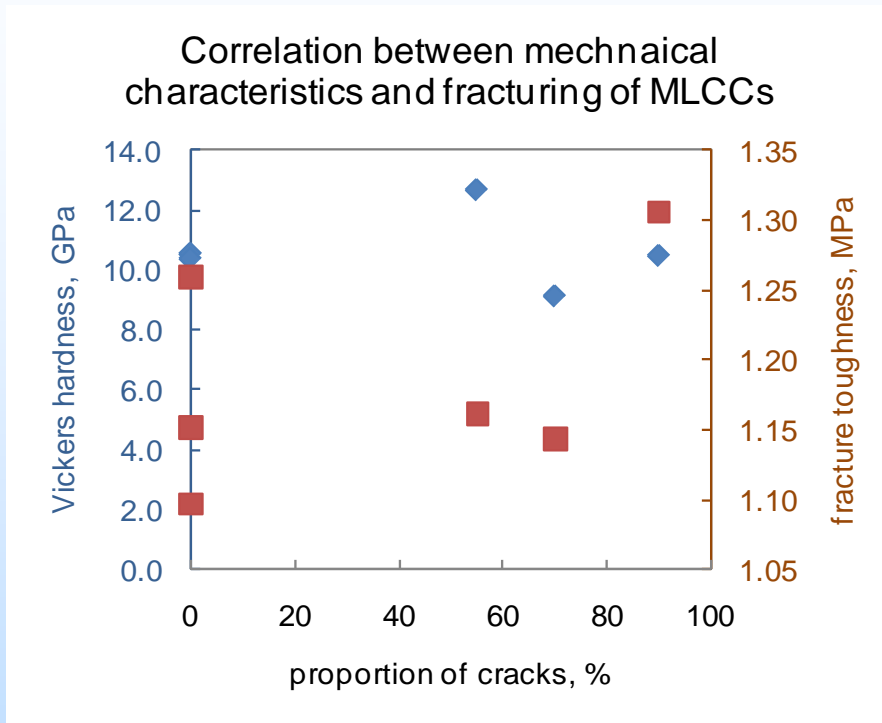


Mechanical Characteristics of MLCCs

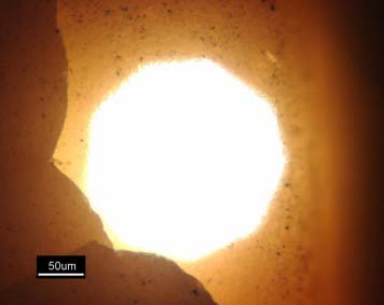
Capacitor	HV, GPa	STD	K1C, MPa-m ^{0.5}	STD
1.0μF, 50 V L1	9.5	1.7	0.91	0.07
100μF, 6.3V	10.6	1.6	1.55	0.09
2.2μF, 50 V	6.5	0.3	1.52	0.14
10μF, 50 V	10.4	1	1.06	0.13
47μF, 16 V	6.6	1.2	1.37	0.08
22nF, 50 V	8.8	0.2	2.81	0.32
22μF, 25 V	8.2	1	1.47	0.07
1.0μF, 50 V L2	9.2	0.9	1.14	0.18
1.0μF, 50 V L3	10.5	0.6	1.15	0.05
0.1μF, 100 V L1	10.5	2.2	1.26	0.27
0.1μF, 100 V L2	10.5	0.3	1.31	0.11
0.1μF, 100 V L3	12.7	2.0	1.16	0.23
0.1μF, 100 V L4	10.4	1.4	1.10	0.09

- Hardness of different types of capacitors varied from 6.5 GPa to 12.7 GPa and did not depend significantly on the type of materials used.
- Estimations of the fracture toughness showed that X7R dielectrics had K1C values in the range from 0.9 to 1.55 MPa-m^{0.5}, whereas capacitors with COG dielectric had a much larger value, 2.8 MPa-m^{0.5}.
- TS robustness of the parts was expected to increase in the sequence 1μF 50V ≈ 10μF 50V < 47μF 16V < 22μF 25V ≈ 2.2μF 50V ≈ 100μF 6V << 22nF 50V.

Correlation between Mechanical Characteristics and TS Testing



- ❑ Different lots had statistically different proportion of cracks after thermal shock testing (TSD-350).
- ❑ No correlation between the probability of fracturing and hardness or fracture toughness.



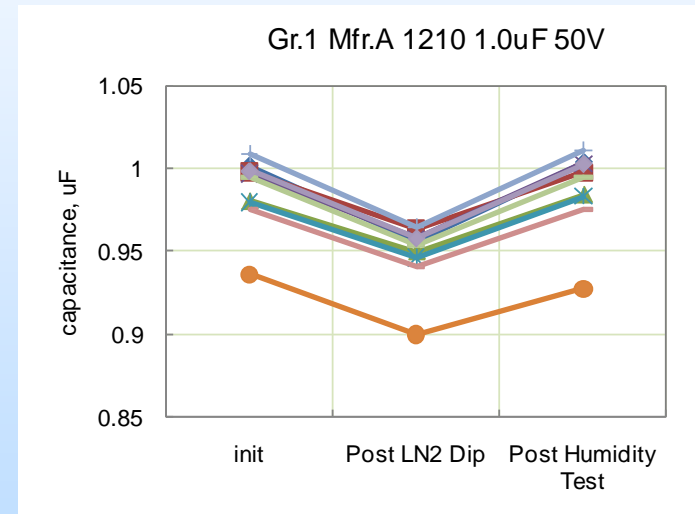
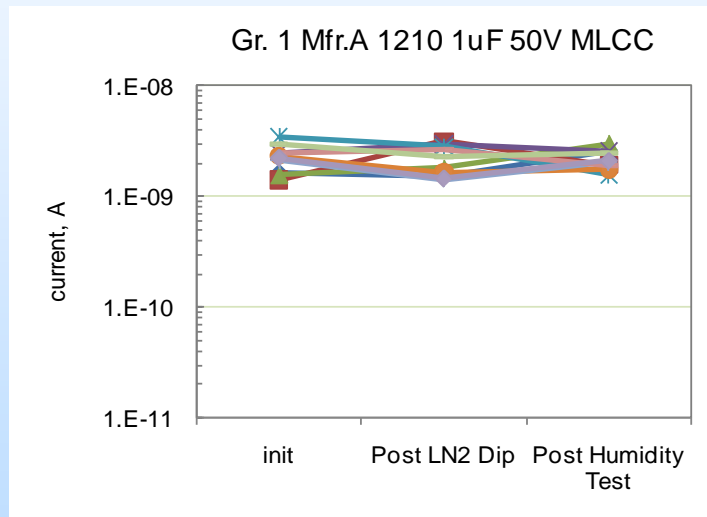
Thermal Shock Methods that Create TS Conditions

Technique	Conditions	Parts	ΔT
Terminal Solder Dip (TSD)	<ul style="list-style-type: none"> •Solder pot temperature 300 °C, 325 °C, 350 °C. •Cooling in air for 3m. •Repeat 10 times 	<ul style="list-style-type: none"> •13 lots from 3 Mfr •1uF 50V, X7R •Size from 1825 to 2225 	275 °C to 325 °C
Ice Water Test (IWT)	<ul style="list-style-type: none"> •Preheat parts at 150 °C to 225 °C •Drop in water at 0 °C 	<ul style="list-style-type: none"> •14 part types from 4 Mfr •1uF 50V, 10uF 50V, and 0.1 uF 100V, X7R •Size from 0805 to 2225 	150 °C to 225 °C
Liquid Nitrogen (LN) drop test	<ul style="list-style-type: none"> •Drop into a Dewar with LN 	<ul style="list-style-type: none"> •4 lots of 1uF 50V, X7R •Size from 1210 to 2225 	220 °C

If ΔT is the most important parameter of TS testing, one can expect most failures during TSD test and least during IWT.

Liquid Nitrogen Drop Test

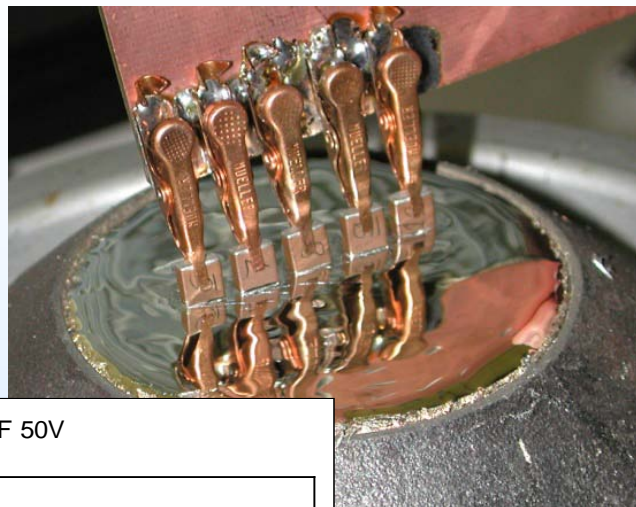
- ❑ 4 types of 1uF 50V capacitors: 1206, 1210, 2220, and 2225.
- ❑ AC and DC characteristics were measured at RT after LN drop and after 10 days at 85°C and 85% RH.



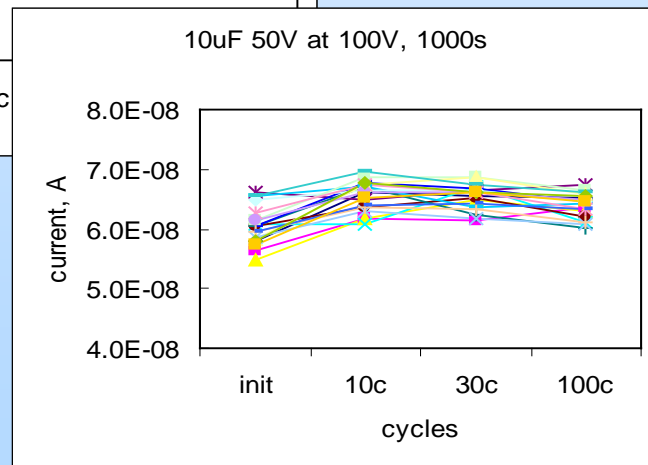
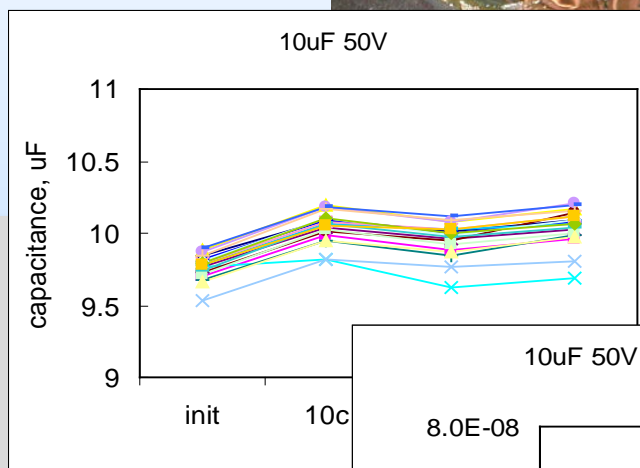
- ❑ No electrical failures or evidence of degradation.
- ❑ A few parts had shallow cracks that were limited to the margin area.
- ❑ Variations in capacitance indicate the effect of mechanical stresses.

Terminal Solder Dip Test, TSD_300

- ❑ Seven lots of 2220 MLCCs with thickness from 1 mm to 3.2 mm, 20 samples each, were subjected to the molten solder (300 °C) terminal dip test.
- ❑ AC and DC characteristics were measured after 10, 30, and 100 solder pot cycles.

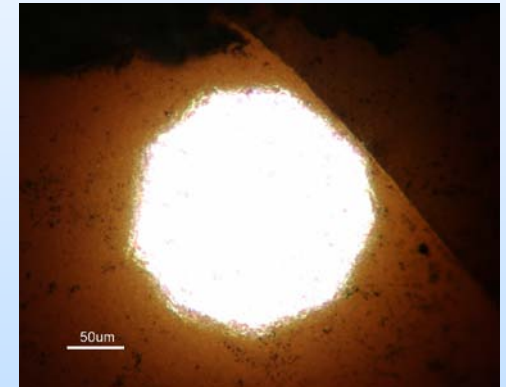
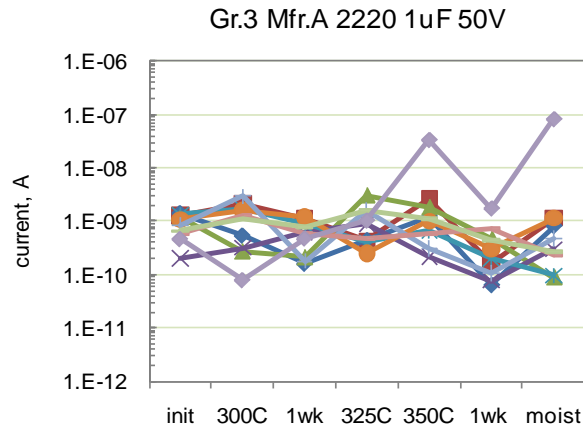
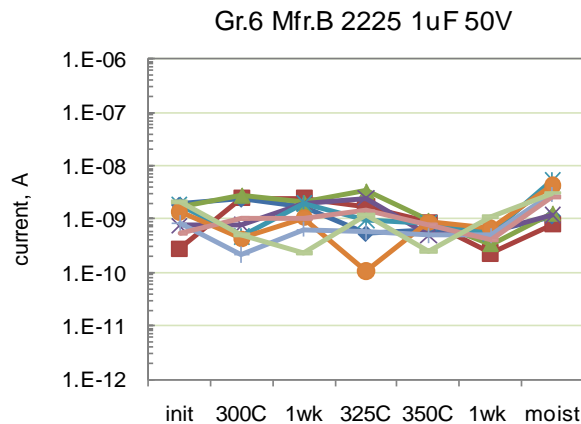


- ❑ No failures or significant parametric variations.
- ❑ Vicinal illumination microscopy revealed no cracking.
- ❑ Normal-quality lots can withstand TSD_300 without fracturing.



Terminal Solder Dip Test, TSD_350

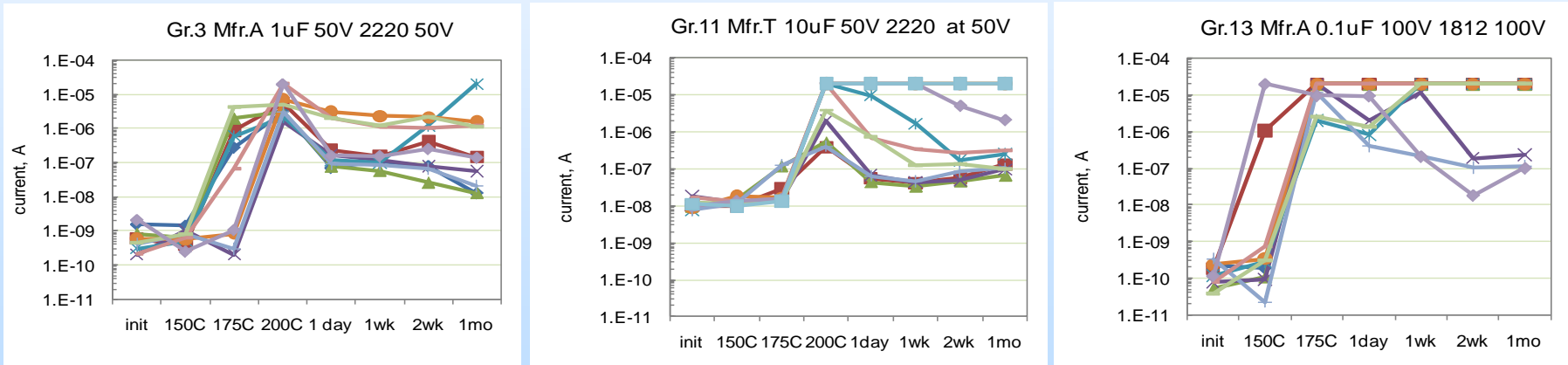
- ❑ Six types of 2220 and 1825 capacitors were stressed by TSD at temperatures from 300 °C to 350 °C in 25 °C increments.
- ❑ Measurements of AC and DC characteristics, and vicinal illumination microscopy were used to reveal cracks.



- ❑ After TSD at 350 °C one out of ten samples in in one out of 7 groups had increased DCL.
- ❑ Three out of six lots had no fractures.
- ❑ Large-size capacitors (2220 and 1825) might have high resistance against thermal stresses developed during soldering.

Ice Water Test

- ❑ Capacitors preheated to T varying from 150 to 225 °C are rapidly quenched in a bath with ice water.
- ❑ Preheat temperature that results in substantial DCL increase is considered as critical, ΔT_c .
- ❑ Based on distribution of ΔT_c , average ΔT_c and STD were calculated to characterize TS resistance of the lot.



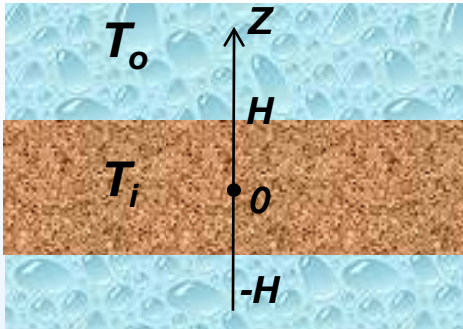
- ❑ Based on IWT of 16 lots of X7R capacitors:
 $\Delta T_{c_min} = 170$ °C and $\Delta T_{c_max} = 222.5$ °C at STD ~ 9.6 °C.
- ❑ Calculated tensile strength is from 110 MPa to 200 MPa.
- ❑ The reproducibility of test results was good, below average STD.

Comparison of TS Test Results

Technique	ΔT	Result
Terminal Solder Dip (TSD)	275 °C to 325 °C	<ul style="list-style-type: none"> • None out of 200 parts from 13 lots had cracks or electrical failures at TSD_300. • Two out of 80 parts from 6 lots failed TSD_350 and samples in 3 lots had from 50% to 90% of “hot TS cracks”.
Ice Water Test (IWT)	150 °C to 225 °C	<ul style="list-style-type: none"> • All 160 parts from 16 lots failed at ΔT below 225 °C. • All parts had “cold TS cracks”.
Liquid Nitrogen (LN) drop test	220 °C	<ul style="list-style-type: none"> • No electrical failures. • Samples in two out of 4 lots had from 20% to 90% of shallow cracks.

- ❑ ΔT is not the major factor affecting thermal shock test results.
- ❑ Results of TS testing are lot-related.

Modeling TS Conditions. T-distributions



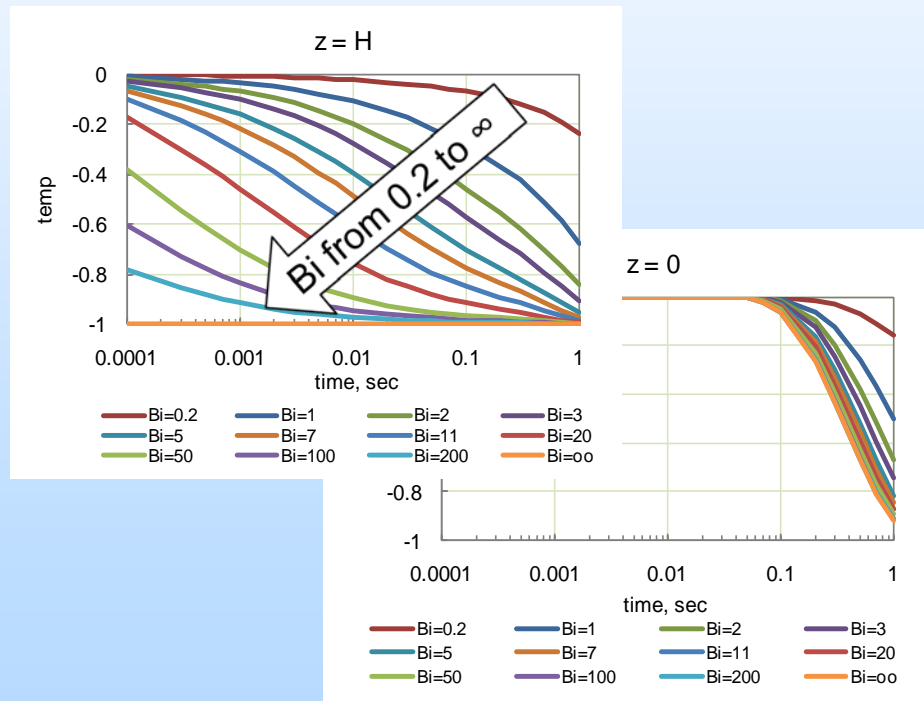
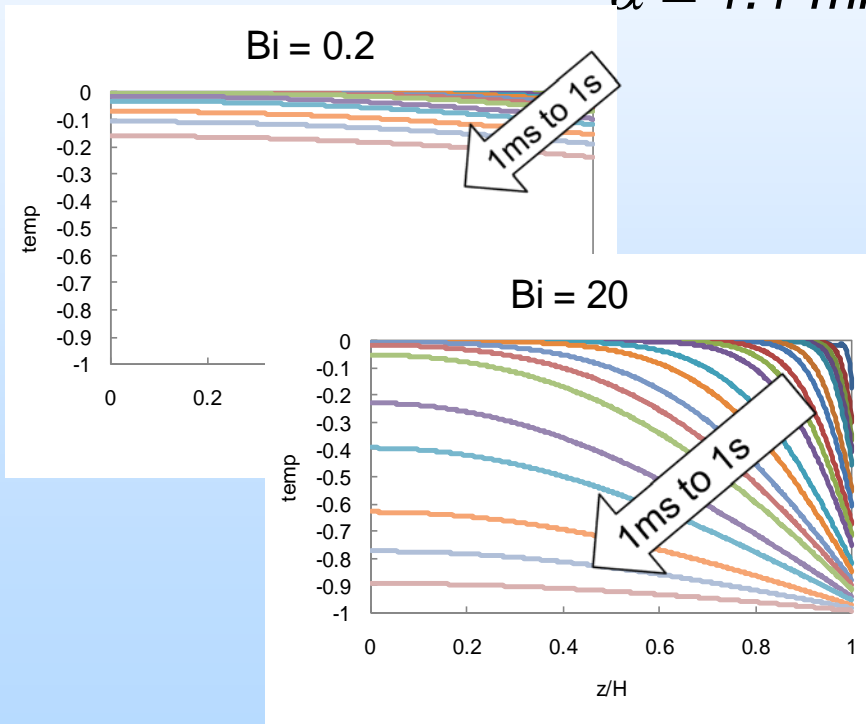
A ceramic plate of thickness $2H$ at $T = T_i$ is immersed in media at $T = T_o$

$$\frac{\partial T}{\partial t} - \alpha \frac{\partial^2 T}{\partial z^2} = 0$$

$$\lambda \frac{\partial T}{\partial z} = -h \times (T_o - T)$$

$$Bi \equiv \frac{h \times H}{\lambda}$$

$$\alpha = 1.1 \text{ mm}^2/\text{sec}, H = 1 \text{ mm}$$



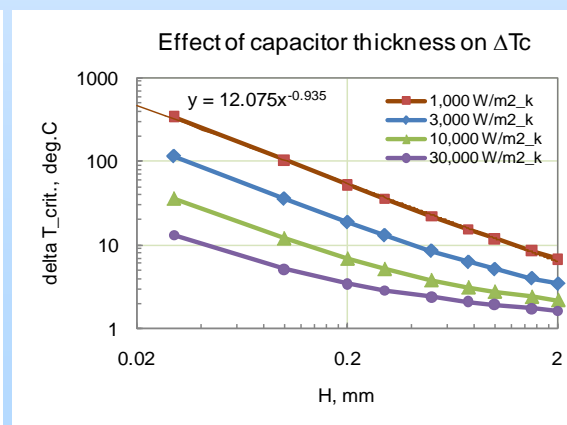
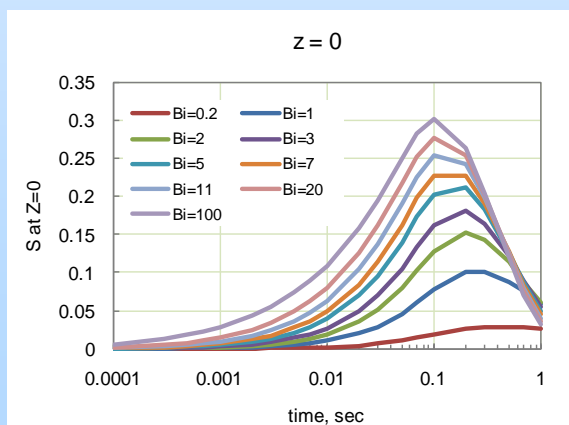
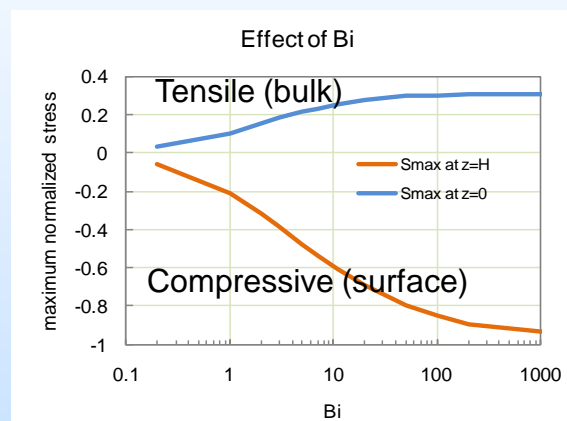
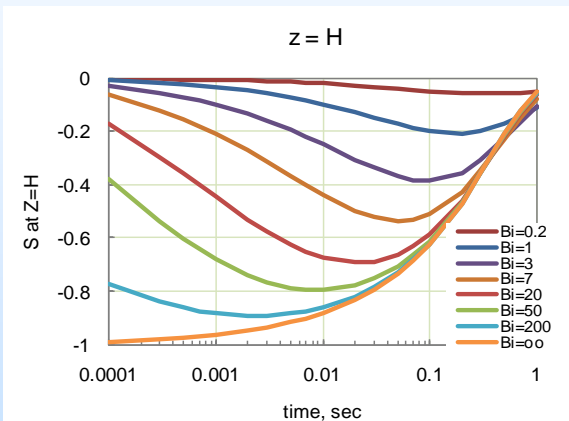
The rate of temperature variations is a strong function of Bi

Modeling TS Stresses

Stress distributions can be calculated based on $T(z,t)$:

$$\sigma(z,t) = -\bar{E} \times \bar{\alpha} \left\{ (T(z,t) - T_i) + \frac{1}{2H} \int_{-H}^H (T(z,t) - T_i) dz \right\}$$

$$\bar{\sigma} = \frac{\sigma(z,t)}{\sigma_{\max}} = \frac{\sigma(z,t)}{E \times \alpha \times (T_i - T_0)}$$



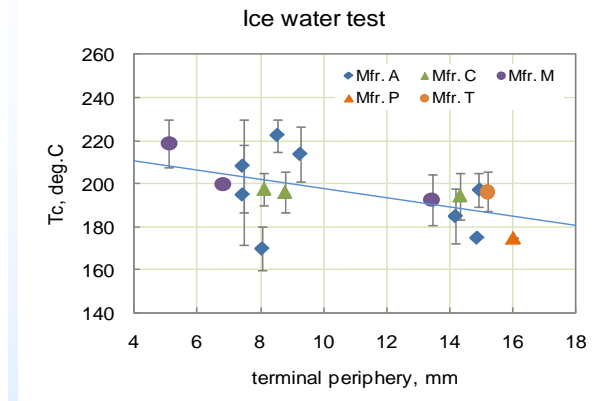
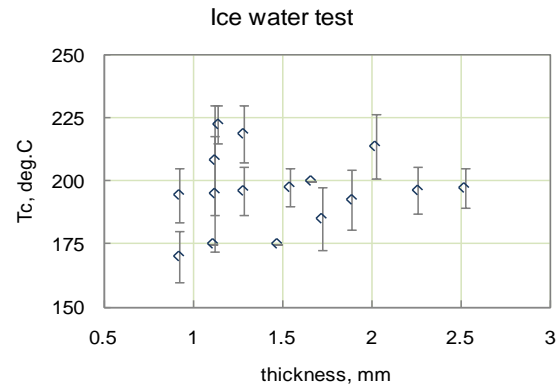
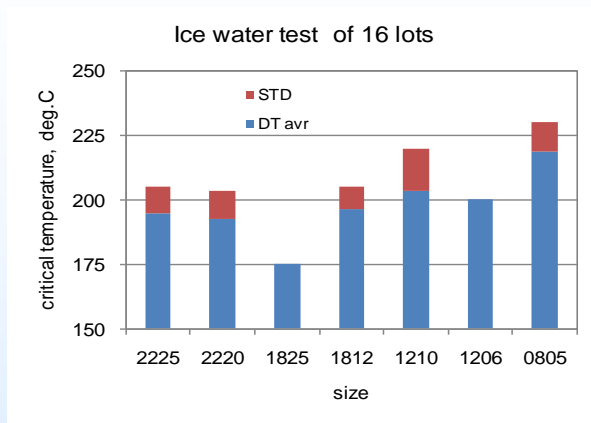
❑ The level of maximum stresses varies substantially with the heat transfer conditions.

❑ During hot TS maximum tensile stresses are much less than compressive.

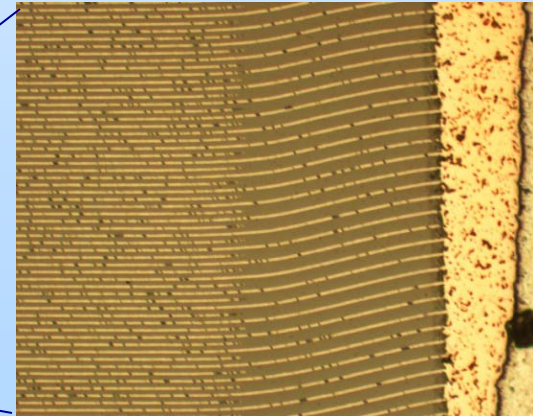
❑ Cold TS is much more stressful than hot TS.

❑ Larger parts experience greater stresses during thermal shock testing.

Effect of Size on Critical Temperature



- ❑ None of the geometrical factors have a strong correlation with the critical temperature measured by IWT.
- ❑ There is a trend of decreasing ΔT_c with the periphery of terminals.
- ❑ The cracks originate mostly at the terminal areas and are likely due to built-in stresses in the parts.



Conclusion/Highlights/Accomplishments

- ❑ Existing MIL-spec requirements do not address properly issues related to the robustness of MLCCs to soldering-induced stresses.
- ❑ The rate of heat transfer, part size, and direction of temperature variations are the most critical parameters of TS testing.
- ❑ Cold TS is more stressful than hot TS because the strength of ceramics to tensile stresses is substantially less than to compressive stresses.
- ❑ Different lots have different susceptibility to soldering-related fracturing. This susceptibility can be evaluated by TSD test.
- ❑ Cracking might occur during post-soldering cooling. IWT is an effective method to quantitatively assess resistance of MLCCs to cold TS.
- ❑ There is a trend of decreasing ΔT_c with the size of periphery of parts. TS resistance of MLCCs depends strongly on the level of built-in stresses.
- ❑ Recommendation. To assure reliable manual soldering:
 - Develop NASA workmanship recommendations/requirements;
 - Test the parts at TSD-300 conditions (guidelines to be developed);
 - Test the parts at specific assembly conditions for critical applications.

List of Acronyms

- MLCC – multilayer ceramic capacitor;
- IWT – ice water testing;
- TSD – terminal solder dip;
- LND – liquid nitrogen drop test;
- LDC – lot date code;
- VH – Vickers hardness;
- STD – standard deviation;
- K1C – in-plane fracture toughness;
- TC – thermal cycling;
- CTE – coefficient of thermal expansion;
- ER – established reliability;
- QCI – quality conformance inspection;
- HV – high voltage;
- RT – room temperature;
- LN – liquid nitrogen;
- RH - relative humidity;
- DCL – direct current leakage;
- T – temperature;
- Bi – Biot modulus;
- h is the coefficient of heat transfer, λ is thermal conductivity, and α is thermal diffusivity.